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## Measurement of the absolute branching fraction of $D^*s_0(2317)^\pm \rightarrow \pi^0 D^\pm s$

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Measurement of the absolute branching fraction of  $D_{s0}^*(2317)^\pm \rightarrow \pi^0 D_s^\pm$ 

M. Ablikim,<sup>1</sup> M. N. Achasov,<sup>9,d</sup> S. Ahmed,<sup>14</sup> M. Albrecht,<sup>4</sup> A. Amoroso,<sup>53a,53c</sup> F. F. An,<sup>1</sup> Q. An,<sup>50,40</sup> J. Z. Bai,<sup>1</sup> Y. Bai,<sup>39</sup> O. Bakina,<sup>24</sup> R. Baldini Ferroli,<sup>20a</sup> Y. Ban,<sup>32</sup> D. W. Bennett,<sup>19</sup> J. V. Bennett,<sup>5</sup> N. Berger,<sup>23</sup> M. Bertani,<sup>20a</sup> D. Bettoni,<sup>21a</sup> J. M. Bian,<sup>47</sup> F. Bianchi,<sup>53a,53c</sup> E. Boger,<sup>24,b</sup> I. Boyko,<sup>24</sup> R. A. Briere,<sup>5</sup> H. Cai,<sup>55</sup> X. Cai,<sup>1,40</sup> O. Cakir,<sup>43a</sup> A. Calcaterra,<sup>20a</sup> G. F. Cao,<sup>1,44</sup> S. A. Cetin,<sup>43b</sup> J. Chai,<sup>53c</sup> J. F. Chang,<sup>1,40</sup> G. Chelkov,<sup>24,b,c</sup> G. Chen,<sup>1</sup> H. S. Chen,<sup>1,44</sup> J. C. Chen,<sup>1</sup> M. L. Chen,<sup>1,40</sup> P. L. Chen,<sup>51</sup> S. J. Chen,<sup>30</sup> X. R. Chen,<sup>27</sup> Y. B. Chen,<sup>1,40</sup> X. K. Chu,<sup>32</sup> G. Cibinetto,<sup>21a</sup> H. L. Dai,<sup>1,40</sup> J. P. Dai,<sup>35,h</sup> A. Dbeyssi,<sup>14</sup> D. Dedovich,<sup>24</sup> Z. Y. Deng,<sup>1</sup> A. Denig,<sup>23</sup> I. Denysenko,<sup>24</sup> M. Destefanis,<sup>53a,53c</sup> F. De Mori,<sup>53a,53c</sup> Y. Ding,<sup>28</sup> C. Dong,<sup>31</sup> J. Dong,<sup>1,40</sup> L. Y. Dong,<sup>1,44</sup> M. Y. Dong,<sup>1,40,44</sup> Z. L. Dou,<sup>30</sup> S. X. Du,<sup>57</sup> P. F. Duan,<sup>1</sup> J. Fang,<sup>1,40</sup> S. S. Fang,<sup>1,44</sup> X. Fang,<sup>50,40</sup> Y. Fang,<sup>1</sup> R. Farinelli,<sup>21a,21b</sup> L. Fava,<sup>53b,53c</sup> S. Fegan,<sup>23</sup> F. Feldbauer,<sup>23</sup> G. Felici,<sup>20a</sup> C. Q. Feng,<sup>50,40</sup> E. Fioravanti,<sup>21a</sup> M. Fritsch,<sup>23,14</sup> C. D. Fu,<sup>1</sup> Q. Gao,<sup>1</sup> X. L. Gao,<sup>50,40</sup> Y. Gao,<sup>42</sup> Y. G. Gao,<sup>6</sup> Z. Gao,<sup>50,40</sup> I. Garzia,<sup>21a</sup> K. Goetzen,<sup>10</sup> L. Gong,<sup>31</sup> W. X. Gong,<sup>1,40</sup> W. Gradl,<sup>23</sup> M. Greco,<sup>53a,53c</sup> M. H. Gu,<sup>1,40</sup> S. Gu,<sup>15</sup> Y. T. Gu,<sup>12</sup> A. Q. Guo,<sup>1</sup> L. B. Guo,<sup>29</sup> R. P. Guo,<sup>1,44</sup> Y. P. Guo,<sup>23</sup> Z. Haddadi,<sup>26</sup> S. Han,<sup>55</sup> X. Q. Hao,<sup>15</sup> F. A. Harris,<sup>45</sup> K. L. He,<sup>1,44</sup> X. Q. He,<sup>49</sup> F. H. Heinsius,<sup>4</sup> T. Held,<sup>4</sup> Y. K. Heng,<sup>1,40,44</sup> T. Holtmann,<sup>4</sup> Z. L. Hou,<sup>1</sup> C. Hu,<sup>29</sup> H. M. Hu,<sup>1,44</sup> T. Hu,<sup>1,40,44</sup> Y. Hu,<sup>1</sup> G. S. Huang,<sup>50,40</sup> J. S. Huang,<sup>15</sup> X. T. Huang,<sup>34</sup> X. Z. Huang,<sup>30</sup> Z. L. Huang,<sup>28</sup> T. Hussain,<sup>52</sup> W. Ikegami Andersson,<sup>54</sup> Q. Ji,<sup>1</sup> Q. P. Ji,<sup>15</sup> X. B. Ji,<sup>1,44</sup> X. L. Ji,<sup>1,40</sup> X. S. Jiang,<sup>1,40,44</sup> X. Y. Jiang,<sup>31</sup> J. B. Jiao,<sup>34</sup> Z. Jiao,<sup>17</sup> D. P. Jin,<sup>1,40,44</sup> S. Jin,<sup>1,44</sup> Y. Jin,<sup>46</sup> T. Johansson,<sup>54</sup> A. Julin,<sup>47</sup> N. Kalantar-Nayestanaki,<sup>26</sup> X. L. Kang,<sup>1</sup> X. S. Kang,<sup>31</sup> M. Kavatsyuk,<sup>26</sup> B. C. Ke,<sup>5</sup> T. Khan,<sup>50,40</sup> A. Khoukaz,<sup>48</sup> P. Kiese,<sup>23</sup> R. Kliemt,<sup>10</sup> L. Koch,<sup>25</sup> O. B. Kolcu,<sup>43b,f</sup> B. Kopf,<sup>4</sup> M. Kornicer,<sup>45</sup> M. Kuemmel,<sup>4</sup> M. Kuessner,<sup>4</sup> M. Kuhlmann,<sup>4</sup> A. Kupsc,<sup>54</sup> W. Kühn,<sup>25</sup> J. S. Lange,<sup>25</sup> M. Lara,<sup>19</sup> P. Larin,<sup>14</sup> L. Lavezzi,<sup>53c</sup> S. Leiber,<sup>4</sup> H. Leithoff,<sup>23</sup> C. Leng,<sup>53c</sup> C. Li,<sup>54</sup> Cheng Li,<sup>50,40</sup> D. M. Li,<sup>57</sup> F. Li,<sup>1,40</sup> F. Y. Li,<sup>32</sup> G. Li,<sup>1</sup> H. B. Li,<sup>1,44</sup> H. J. Li,<sup>1,44</sup> J. C. Li,<sup>1</sup> J. Q. Li,<sup>4</sup> K. J. Li,<sup>41</sup> Kang Li,<sup>13</sup> Ke Li,<sup>1</sup> Lei Li,<sup>3</sup> P. L. Li,<sup>50,40</sup> P. R. Li,<sup>44,7</sup> Q. Y. Li,<sup>34</sup> T. Li,<sup>34</sup> W. D. Li,<sup>1,44</sup> W. G. Li,<sup>1</sup> X. L. Li,<sup>34</sup> X. N. Li,<sup>1,40</sup> X. Q. Li,<sup>31</sup> Z. B. Li,<sup>41</sup> H. Liang,<sup>50,40</sup> Y. F. Liang,<sup>37</sup> Y. T. Liang,<sup>25</sup> G. R. Liao,<sup>11</sup> D. X. Lin,<sup>14</sup> B. Liu,<sup>35,h</sup> B. J. Liu,<sup>1</sup> C. X. Liu,<sup>1</sup> D. Liu,<sup>50,40</sup> F. H. Liu,<sup>36</sup> Fang Liu,<sup>1</sup> Feng Liu,<sup>6</sup> H. B. Liu,<sup>12</sup> H. M. Liu,<sup>1,44</sup> Huanhuan Liu,<sup>1</sup> Huihui Liu,<sup>16</sup> J. B. Liu,<sup>50,40</sup> J. P. Liu,<sup>55</sup> J. Y. Liu,<sup>1,44</sup> K. Liu,<sup>42</sup> K. Y. Liu,<sup>28</sup> Ke Liu,<sup>6</sup> L. D. Liu,<sup>32</sup> P. L. Liu,<sup>1,40</sup> Q. Liu,<sup>44</sup> S. B. Liu,<sup>50,40</sup> X. Liu,<sup>27</sup> Y. B. Liu,<sup>31</sup> Z. A. Liu,<sup>1,40,44</sup> Zhiqing Liu,<sup>23</sup> Y. F. Long,<sup>32</sup> X. C. Lou,<sup>1,40,44</sup> H. J. Lu,<sup>17</sup> J. G. Lu,<sup>1,40</sup> Y. Lu,<sup>1</sup> Y. P. Lu,<sup>1,40</sup> C. L. Luo,<sup>29</sup> M. X. Luo,<sup>56</sup> X. L. Luo,<sup>1,40</sup> X. R. Lyu,<sup>44</sup> F. C. Ma,<sup>28</sup> H. L. Ma,<sup>1</sup> L. L. Ma,<sup>34</sup> M. M. Ma,<sup>1,44</sup> Q. M. Ma,<sup>1</sup> T. Ma,<sup>1</sup> X. N. Ma,<sup>31</sup> X. Y. Ma,<sup>1,40</sup> Y. M. Ma,<sup>34</sup> F. E. Maas,<sup>14</sup> M. Maggiora,<sup>53a,53c</sup> Q. A. Malik,<sup>52</sup> Y. J. Mao,<sup>32</sup> Z. P. Mao,<sup>1</sup> S. Marcello,<sup>53a,53c</sup> Z. X. Meng,<sup>46</sup> J. G. Messchendorp,<sup>26</sup> G. Mezzadri,<sup>21b</sup> J. Min,<sup>1,40</sup> T. J. Min,<sup>1</sup> R. E. Mitchell,<sup>19</sup> X. H. Mo,<sup>1,40,44</sup> Y. J. Mo,<sup>6</sup> C. Morales Morales,<sup>14</sup> G. Morello,<sup>20a</sup> N. Yu. Muchnoi,<sup>9,d</sup> H. Muramatsu,<sup>47</sup> P. Musiol,<sup>4</sup> A. Mustafa,<sup>4</sup> Y. Nefedov,<sup>24</sup> F. Nerling,<sup>10</sup> I. B. Nikolaev,<sup>9,d</sup> Z. Ning,<sup>1,40</sup> S. Nisar,<sup>8</sup> S. L. Niu,<sup>1,40</sup> X. Y. Niu,<sup>1,44</sup> S. L. Olsen,<sup>33,j</sup> Q. Ouyang,<sup>1,40,44</sup> S. Pacetti,<sup>20b</sup> Y. Pan,<sup>50,40</sup> M. Papenbrock,<sup>54</sup> P. Patteri,<sup>20a</sup> M. Pelizaeus,<sup>4</sup> J. Pellegrino,<sup>53a,53c</sup> H. P. Peng,<sup>50,40</sup> K. Peters,<sup>10,g</sup> J. Pettersson,<sup>54</sup> J. L. Ping,<sup>29</sup> R. G. Ping,<sup>1,44</sup> A. Pitka,<sup>23</sup> R. Poling,<sup>47</sup> V. Prasad,<sup>50,40</sup> H. R. Qi,<sup>2</sup> M. Qi,<sup>30</sup> S. Qian,<sup>1,40</sup> C. F. Qiao,<sup>44</sup> N. Qin,<sup>55</sup> X. S. Qin,<sup>4</sup> Z. H. Qin,<sup>1,40</sup> J. F. Qiu,<sup>1</sup> K. H. Rashid,<sup>52,i</sup> C. F. Redmer,<sup>23</sup> M. Richter,<sup>4</sup> M. Ripka,<sup>23</sup> M. Rolo,<sup>53c</sup> G. Rong,<sup>1,44</sup> Ch. Rosner,<sup>14</sup> X. D. Ruan,<sup>12</sup> A. Sarantsev,<sup>24,e</sup> M. Savrié,<sup>21b</sup> C. Schnier,<sup>4</sup> K. Schoenning,<sup>54</sup> W. Shan,<sup>32</sup> M. Shao,<sup>50,40</sup> C. P. Shen,<sup>2</sup> P. X. Shen,<sup>31</sup> X. Y. Shen,<sup>1,44</sup> H. Y. Sheng,<sup>1</sup> J. J. Song,<sup>34</sup> W. M. Song,<sup>34</sup> X. Y. Song,<sup>1</sup> S. Sosio,<sup>53a,53c</sup> C. Sowa,<sup>4</sup> S. Spataro,<sup>53a,53c</sup> G. X. Sun,<sup>1</sup> J. F. Sun,<sup>15</sup> L. Sun,<sup>55</sup> S. S. Sun,<sup>1,44</sup> X. H. Sun,<sup>1</sup> Y. J. Sun,<sup>50,40</sup> Y. K. Sun,<sup>50,40</sup> Y. Z. Sun,<sup>1</sup> Z. J. Sun,<sup>1,40</sup> Z. T. Sun,<sup>19</sup> C. J. Tang,<sup>37</sup> G. Y. Tang,<sup>1</sup> X. Tang,<sup>1</sup> I. Tapan,<sup>43c</sup> M. Tiemens,<sup>26</sup> B. Tsednee,<sup>22</sup> I. Uman,<sup>43d</sup> G. S. Varner,<sup>45</sup> B. Wang,<sup>1</sup> B. L. Wang,<sup>44</sup> D. Wang,<sup>32</sup> D. Y. Wang,<sup>32</sup> Dan Wang,<sup>44</sup> K. Wang,<sup>1,40</sup> L. L. Wang,<sup>1</sup> L. S. Wang,<sup>1</sup> M. Wang,<sup>34</sup> Meng Wang,<sup>1,44</sup> P. Wang,<sup>1</sup> P. L. Wang,<sup>1</sup> W. P. Wang,<sup>50,40</sup> X. F. Wang,<sup>42</sup> Y. Wang,<sup>38</sup> Y. D. Wang,<sup>14</sup> Y. F. Wang,<sup>1,40,44</sup> Y. Q. Wang,<sup>23</sup> Z. Wang,<sup>1,40</sup> Z. G. Wang,<sup>1,40</sup> Z. H. Wang,<sup>50,40</sup> Z. Y. Wang,<sup>1</sup> Zongyuan Wang,<sup>1,44</sup> T. Weber,<sup>23</sup> D. H. Wei,<sup>11</sup> P. Weidenkaff,<sup>23</sup> S. P. Wen,<sup>1</sup> U. Wiedner,<sup>4</sup> M. Wolke,<sup>54</sup> L. H. Wu,<sup>1</sup> L. J. Wu,<sup>1,44</sup> Z. Wu,<sup>1,40</sup> L. Xia,<sup>50,40</sup> X. Xia,<sup>34</sup> Y. Xia,<sup>18</sup> D. Xiao,<sup>1</sup> H. Xiao,<sup>51</sup> Y. J. Xiao,<sup>1,44</sup> Z. J. Xiao,<sup>29</sup> Y. G. Xie,<sup>1,40</sup> Y. H. Xie,<sup>6</sup> X. A. Xiong,<sup>1,44</sup> Q. L. Xiu,<sup>1,40</sup> G. F. Xu,<sup>1</sup> J. J. Xu,<sup>1,44</sup> L. Xu,<sup>1</sup> Q. J. Xu,<sup>13</sup> Q. N. Xu,<sup>44</sup> X. P. Xu,<sup>38</sup> L. Yan,<sup>53a,53c</sup> W. B. Yan,<sup>50,40</sup> W. C. Yan,<sup>50,40</sup> W. C. Yan,<sup>2</sup> Y. H. Yan,<sup>18</sup> H. J. Yang,<sup>35,h</sup> H. X. Yang,<sup>1</sup> L. Yang,<sup>55</sup> Y. H. Yang,<sup>30</sup> Y. X. Yang,<sup>11</sup> Yifan Yang,<sup>1,44</sup> M. Ye,<sup>1,40</sup> M. H. Ye,<sup>7</sup> J. H. Yin,<sup>1</sup> Z. Y. You,<sup>41</sup> B. X. Yu,<sup>1,40,44</sup> C. X. Yu,<sup>31</sup> J. S. Yu,<sup>27</sup> C. Z. Yuan,<sup>1,44</sup> Y. Yuan,<sup>1</sup> A. Yuncu,<sup>43b,a</sup> A. A. Zafar,<sup>52</sup> A. Zallo,<sup>20a</sup> Y. Zeng,<sup>18</sup> Z. Zeng,<sup>50,40</sup> B. X. Zhang,<sup>1</sup> B. Y. Zhang,<sup>1,40</sup> C. C. Zhang,<sup>1</sup> D. H. Zhang,<sup>1</sup> H. H. Zhang,<sup>41</sup> H. Y. Zhang,<sup>1,40</sup> J. Zhang,<sup>1,44</sup> J. L. Zhang,<sup>1</sup> J. Q. Zhang,<sup>1</sup> J. W. Zhang,<sup>1,40,44</sup> J. Y. Zhang,<sup>1</sup> J. Z. Zhang,<sup>1,44</sup> K. Zhang,<sup>1,44</sup> L. Zhang,<sup>42</sup> S. Q. Zhang,<sup>31</sup> X. Y. Zhang,<sup>34</sup> Y. H. Zhang,<sup>1,40</sup> Y. T. Zhang,<sup>50,40</sup> Yang Zhang,<sup>1</sup> Yao Zhang,<sup>1</sup> Yu Zhang,<sup>44</sup> Z. H. Zhang,<sup>6</sup> Z. P. Zhang,<sup>50</sup> Z. Y. Zhang,<sup>55</sup> G. Zhao,<sup>1</sup> J. W. Zhao,<sup>1,40</sup> J. Y. Zhao,<sup>1,44</sup> J. Z. Zhao,<sup>1,40</sup> Lei Zhao,<sup>50,40</sup> Ling Zhao,<sup>1</sup> M. G. Zhao,<sup>31</sup> Q. Zhao,<sup>1</sup> S. J. Zhao,<sup>57</sup> T. C. Zhao,<sup>1</sup> Y. B. Zhao,<sup>1,40</sup> Z. G. Zhao,<sup>50,40</sup>

A. Zhemchugov,<sup>24,b</sup> B. Zheng,<sup>51</sup> J. P. Zheng,<sup>1,40</sup> W. J. Zheng,<sup>34</sup> Y. H. Zheng,<sup>44</sup> B. Zhong,<sup>29</sup> L. Zhou,<sup>1,40</sup> X. Zhou,<sup>55</sup>  
 X. K. Zhou,<sup>50,40</sup> X. R. Zhou,<sup>50,40</sup> X. Y. Zhou,<sup>1</sup> Y. X. Zhou,<sup>12</sup> J. Zhu,<sup>31</sup> J. Zhu,<sup>41</sup> K. Zhu,<sup>1</sup> K. J. Zhu,<sup>1,40,44</sup> S. Zhu,<sup>1</sup> S. H. Zhu,<sup>49</sup>  
 X. L. Zhu,<sup>42</sup> Y. C. Zhu,<sup>50,40</sup> Y. S. Zhu,<sup>1,44</sup> Z. A. Zhu,<sup>1,44</sup> J. Zhuang,<sup>1,40</sup> B. S. Zou,<sup>1</sup> and J. H. Zou<sup>1</sup>

(BESIII Collaboration)

- <sup>1</sup>*Institute of High Energy Physics, Beijing 100049, People's Republic of China*  
<sup>2</sup>*Beihang University, Beijing 100191, People's Republic of China*  
<sup>3</sup>*Beijing Institute of Petrochemical Technology, Beijing 102617, People's Republic of China*  
<sup>4</sup>*Bochum Ruhr-University, D-44780 Bochum, Germany*  
<sup>5</sup>*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*  
<sup>6</sup>*Central China Normal University, Wuhan 430079, People's Republic of China*  
<sup>7</sup>*China Center of Advanced Science and Technology, Beijing 100190, People's Republic of China*  
<sup>8</sup>*COMSATS Institute of Information Technology, Lahore, Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan*  
<sup>9</sup>*G.I. Budker Institute of Nuclear Physics SB RAS (BINP), Novosibirsk 630090, Russia*  
<sup>10</sup>*GSI Helmholtzcentre for Heavy Ion Research GmbH, D-64291 Darmstadt, Germany*  
<sup>11</sup>*Guangxi Normal University, Guilin 541004, People's Republic of China*  
<sup>12</sup>*Guangxi University, Nanning 530004, People's Republic of China*  
<sup>13</sup>*Hangzhou Normal University, Hangzhou 310036, People's Republic of China*  
<sup>14</sup>*Helmholtz Institute Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany*  
<sup>15</sup>*Henan Normal University, Xinxing 453007, People's Republic of China*  
<sup>16</sup>*Henan University of Science and Technology, Luoyang 471003, People's Republic of China*  
<sup>17</sup>*Huangshan College, Huangshan 245000, People's Republic of China*  
<sup>18</sup>*Hunan University, Changsha 410082, People's Republic of China*  
<sup>19</sup>*Indiana University, Bloomington, Indiana 47405, USA*  
<sup>20a</sup>*INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy*  
<sup>20b</sup>*INFN and University of Perugia, I-06100 Perugia, Italy*  
<sup>21a</sup>*INFN Sezione di Ferrara, I-44122 Ferrara, Italy*  
<sup>21b</sup>*University of Ferrara, I-44122 Ferrara, Italy*  
<sup>22</sup>*Institute of Physics and Technology, Peace Avenue 54B, Ulaanbaatar 13330, Mongolia*  
<sup>23</sup>*Johannes Gutenberg University of Mainz, Johann-Joachim-Becher-Weg 45, D-55099 Mainz, Germany*  
<sup>24</sup>*Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia*  
<sup>25</sup>*Justus-Liebig-Universitaet Giessen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany*  
<sup>26</sup>*KVI-CART, University of Groningen, NL-9747 AA Groningen, The Netherlands*  
<sup>27</sup>*Lanzhou University, Lanzhou 730000, People's Republic of China*  
<sup>28</sup>*Liaoning University, Shenyang 110036, People's Republic of China*  
<sup>29</sup>*Nanjing Normal University, Nanjing 210023, People's Republic of China*  
<sup>30</sup>*Nanjing University, Nanjing 210093, People's Republic of China*  
<sup>31</sup>*Nankai University, Tianjin 300071, People's Republic of China*  
<sup>32</sup>*Peking University, Beijing 100871, People's Republic of China*  
<sup>33</sup>*Seoul National University, Seoul 151-747, Korea*  
<sup>34</sup>*Shandong University, Jinan 250100, People's Republic of China*  
<sup>35</sup>*Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China*  
<sup>36</sup>*Shanxi University, Taiyuan 030006, People's Republic of China*  
<sup>37</sup>*Sichuan University, Chengdu 610064, People's Republic of China*  
<sup>38</sup>*Soochow University, Suzhou 215006, People's Republic of China*  
<sup>39</sup>*Southeast University, Nanjing 211100, People's Republic of China*  
<sup>40</sup>*State Key Laboratory of Particle Detection and Electronics, Beijing 100049, Hefei 230026, People's Republic of China*  
<sup>41</sup>*Sun Yat-Sen University, Guangzhou 510275, People's Republic of China*  
<sup>42</sup>*Tsinghua University, Beijing 100084, People's Republic of China*  
<sup>43a</sup>*Ankara University, 06100 Tandogan, Ankara, Turkey*  
<sup>43b</sup>*Istanbul Bilgi University, 34060 Eyup, Istanbul, Turkey*  
<sup>43c</sup>*Uludag University, 16059 Bursa, Turkey*  
<sup>43d</sup>*Near East University, Nicosia, North Cyprus, Mersin 10, Turkey*  
<sup>44</sup>*University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*  
<sup>45</sup>*University of Hawaii, Honolulu, Hawaii 96822, USA*

<sup>46</sup>University of Jinan, Jinan 250022, People's Republic of China<sup>47</sup>University of Minnesota, Minneapolis, Minnesota 55455, USA<sup>48</sup>University of Muenster, Wilhelm-Klemm-Str. 9, 48149 Muenster, Germany<sup>49</sup>University of Science and Technology Liaoning, Anshan 114051, People's Republic of China<sup>50</sup>University of Science and Technology of China, Hefei 230026, People's Republic of China<sup>51</sup>University of South China, Hengyang 421001, People's Republic of China<sup>52</sup>University of the Punjab, Lahore 54590, Pakistan<sup>53a</sup>University of Turin, I-10125 Turin, Italy<sup>53b</sup>University of Eastern Piedmont, I-15121 Alessandria, Italy<sup>53c</sup>INFN, I-10125 Turin, Italy<sup>54</sup>Uppsala University, Box 516, SE-75120 Uppsala, Sweden<sup>55</sup>Wuhan University, Wuhan 430072, People's Republic of China<sup>56</sup>Zhejiang University, Hangzhou 310027, People's Republic of China<sup>57</sup>Zhengzhou University, Zhengzhou 450001, People's Republic of China

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The process  $e^+e^- \rightarrow D_s^{*+}D_{s0}^*(2317)^- + \text{c.c.}$  is observed for the first time with the data sample of  $567 \text{ pb}^{-1}$  collected with the BESIII detector operating at the BEPCII collider at a center-of-mass energy  $\sqrt{s} = 4.6 \text{ GeV}$ . The statistical significance of the  $D_{s0}^*(2317)^\pm$  signal is  $5.8\sigma$  and the mass is measured to be  $(2318.3 \pm 1.2 \pm 1.2) \text{ MeV}/c^2$ . The absolute branching fraction  $\mathcal{B}(D_{s0}^*(2317)^\pm \rightarrow \pi^0 D_s^\pm)$  is measured as  $1.00^{+0.00}_{-0.14}(\text{stat})^{+0.00}_{-0.14}(\text{syst})$  for the first time. The uncertainties are statistical and systematic, respectively.

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## I. INTRODUCTION

The  $D_{s0}^*(2317)^-$  meson<sup>1</sup> was first observed at the *BABAR* experiment via its decay to  $\pi^0 D_s^-$  [1,2]; it was subsequently confirmed at the CLEO [3] and Belle [4] experiments. The  $D_{s0}^*(2317)^-$  meson is suggested to be the  $P$ -wave  $\bar{c}s$  state with spin-parity  $J^P = 0^+$ . However, the measured mass

$(2317.7 \pm 0.6) \text{ MeV}/c^2$  [5] is at least  $150 \text{ MeV}/c^2$  lower than the calculations of a potential model [6] and lattice QCD [7] for the conventional  $\bar{c}s$  state, but it can be explained by introducing other effects. As the  $D_{s0}^*(2317)^-$  is  $45 \text{ MeV}/c^2$  below the  $DK$  threshold, it has been proposed as a good candidate for a  $DK$  molecule [8], a  $\bar{c}s q\bar{q}$  tetraquark state [9], one of the chiral charmed doublets [10], or a mixture of a  $\bar{c}s$  meson and a  $\bar{c}s q\bar{q}$  tetraquark [11].

The  $D_{s0}^*(2317)^-$  is extremely narrow, and the upper limit on its width is  $3.8 \text{ MeV}$  at the 95% confidence level (C.L.) [12]. The only known decay is the isospin-violating mode  $\pi^0 D_s^-$ , and no branching fraction or partial width of this mode has been measured. Theoretical calculations give different values for the partial decay width  $\Gamma(D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-)$  based on different assumptions [13–16]. The partial width  $\Gamma(D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-)$  is around  $30 \text{ keV}$  or even as low as a few  $\text{keV}$  if the  $D_{s0}^*(2317)^-$  is a pure  $\bar{c}s$  state, while it can be enhanced by a hundred  $\text{keV}$  or even larger in the molecule picture due to the contribution of meson loops. Therefore, the partial decay width or the branching fraction is a key quantity to identify the nature of  $D_{s0}^*(2317)^-$ .

In this article, we present first observation of  $e^+e^- \rightarrow D_s^{*+}D_{s0}^*(2317)^- + \text{c.c.}$  and the first measurement of the absolute branching fraction of  $D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-$ . The data sample, which corresponds to an integrated luminosity of  $567 \text{ pb}^{-1}$  [17], has been collected at a center-of-mass (c.m.) energy of  $4.6 \text{ GeV}$  [18]. In this analysis, a  $D_s^{*+}$  is reconstructed via its  $\gamma D_s^+$  decay with  $D_s^+$  decaying to  $K^+ K^- \pi^+$ , and its recoil mass spectrum is examined to search for a  $D_{s0}^*(2317)^-$  signal. The  $D_s^{*+}$  tagged sample is further divided into two subcategories, one with a tagged  $\pi^0$

<sup>a</sup>Also at Bogazici University, 34342 Istanbul, Turkey.<sup>b</sup>Also at the Moscow Institute of Physics and Technology, Moscow 141700, Russia.<sup>c</sup>Also at the Functional Electronics Laboratory, Tomsk State University, Tomsk 634050, Russia.<sup>d</sup>Also at the Novosibirsk State University, Novosibirsk 630090, Russia.<sup>e</sup>Also at the NRC “Kurchatov Institute,” PNPI, 188300 Gatchina, Russia.<sup>f</sup>Also at Istanbul Arel University, 34295 Istanbul, Turkey.<sup>g</sup>Also at Goethe University Frankfurt, 60323 Frankfurt am Main, Germany.<sup>h</sup>Also at Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology; Institute of Nuclear and Particle Physics, Shanghai 200240, People's Republic of China.<sup>i</sup>Also at Government College Women University, Sialkot-51310, Punjab, Pakistan.<sup>j</sup>Present address: Center for Underground Physics, Institute for Basic Science, Daejeon 34126, Korea.<sup>1</sup>Throughout the text, the inclusion of the charge conjugate mode is implied unless otherwise stated.



and the other with no tagged  $\pi^0$ . By using the numbers of signal events in these two categories, the absolute branching fraction of  $D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-$  is determined.

The remainder of this paper is organized as follows. In Sec. II, the BESIII detector and the MC simulation are described; in Sec. III, the event selections for  $D_s^{*+}$  and  $\pi^0$  are listed; Sec. IV presents the determination of the absolute branching fraction, as well as the measurement of the mass of  $D_{s0}^*(2317)^-$ ; and Sec. V lists the estimation of the corresponding systematic uncertainties. A summary of all results is given in Sec. VI.

## II. BESIII DETECTOR AND MC SIMULATION

The BESIII detector, described in detail in Ref. [19], has a geometrical acceptance of 93% of  $4\pi$ rad. A small-cell helium-based main drift chamber (MDC) provides a charged particle momentum resolution of 0.5% at 1 GeV/c in a 1 T magnetic field, and supplies energy loss ( $dE/dx$ ) measurements with a resolution better than 6% for electrons from Bhabha scattering. The electromagnetic calorimeter (EMC) measures photon energies with a resolution of 2.5% (5%) at 1.0 GeV in the barrel (end caps). Particle identification (PID) is provided by a time-of-flight system (TOF) with a time resolution of 80 ps (110 ps) for the barrel (end caps). The muon system, located in the iron flux return yoke of the magnet, provides 2 cm position resolution and detects muon tracks with momentum greater than 0.5 GeV/c.

In order to determine the detection efficiency and to optimize the selection criteria, the GEANT4-based [20] Monte Carlo (MC) simulation software BOOST [21], which includes the geometric description of the detector and detector responses, is used to simulate  $e^+e^- \rightarrow D_s^{*+} D_{s0}^*(2317)^-$  at  $\sqrt{s} = 4.6$  GeV with  $D_s^{*+} \rightarrow \gamma D_s^+$  and  $D_s^+ \rightarrow K^+ K^- \pi^+$ , and  $D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-$  or  $\gamma D_s^{*-}$ . The  $D_s^-$  and  $D_s^{*-}$  are set to decay inclusively. The  $J^P$  of  $D_{s0}^*(2317)^-$  is  $0^+$ , so it is in relative  $S$ -wave to the  $D_s^{*+}$ , and they are generated uniformly in phase space. The initial state radiation (ISR) is simulated with KKMC [22] using a calculation with a precision better than 0.2%. The final state radiation (FSR) effects associated with charged particles is handled with PHOTOS [23]. To study the possible backgrounds, an inclusive MC sample with an integrated luminosity equivalent to data is generated. All the known charmonium transitions, hadronic decays and open charm channels are modeled with EVTGEN [24,25] incorporating the branching fractions taken from the Particle Data Group [5], while the QED processes and the unknown charmonium decays are generated with BABAYAGA [26] and LUNDCHARM [27], respectively.

## III. EVENT SELECTIONS AND BACKGROUND STUDY

To reconstruct  $D_s^{*+}$ , the  $\gamma D_s^+$  channel is used with  $D_s^+$  decaying to  $K^+ K^- \pi^+$ . Events with at least three charged

track candidates and at least one photon candidate are selected. For each charged track candidate, the polar angle  $\theta$  in the MDC must satisfy  $|\cos \theta| < 0.93$ , and the distance of the closest approach to the  $e^+e^-$  interaction point is required to be less than 10 cm along the beam direction and less than 1 cm in the plane perpendicular to the beam. PID, which uses both the information from TOF and the specific energy loss ( $dE/dx$ ), is performed to separate kaons and pions. The photon candidates are selected from showers in the EMC with deposited energy greater than 25 MeV in the barrel [ $|\cos(\theta)| < 0.8$ ] or greater than 50 MeV in the end-cap regions [ $0.86 < |\cos(\theta)| < 0.92$ ]. To eliminate showers produced by charged tracks, the photon candidate must be separated by at least  $20^\circ$  from any charged track. The time for the shower measured by the EMC from the start of this event is restricted to be less than 700 ns to suppress electronic noise and energy depositions unrelated to the event.

All combinations are required to have the invariant masses of  $K^+ K^- \pi^+$  and  $\gamma K^+ K^- \pi^+$  within  $\Delta M_{K^+ K^- \pi^+} \equiv |M(K^+ K^- \pi^+) - m_{D_s^+}| < 16 \text{ MeV}/c^2$  and  $\Delta M_{\gamma K^+ K^- \pi^+} \equiv |M(\gamma K^+ K^- \pi^+) - m_{D_s^{*+}}| < 11 \text{ MeV}/c^2$ , where  $M((\gamma)K^+ K^- \pi^+)$  is the invariant mass of the  $(\gamma)K^+ K^- \pi^+$  system, and  $m_{D_s^+}$  and  $m_{D_s^{*+}}$  are the nominal masses of  $D_s^+$  and  $D_s^{*+}$  [5], respectively. A two-constraint (2C) kinematic fit is performed on the surviving events with the mass constraints of  $D_s$  and  $D_s^*$  to obtain a better recoil mass resolution and to suppress backgrounds. The  $\chi^2_{2C}$  from the kinematic fit is required to be less than 14. All successful combinations in each event are kept for further study.

After the previously described selection criteria, the recoil mass distribution of  $D_s^{*+}$  is shown in Fig. 1, where a  $D_{s0}^*(2317)^-$  signal can be observed. The events in the sidebands of  $D_s^+$  and  $D_s^{*+}$  in the sample before the kinematic fit are checked and no signal of  $D_{s0}^*(2317)^-$

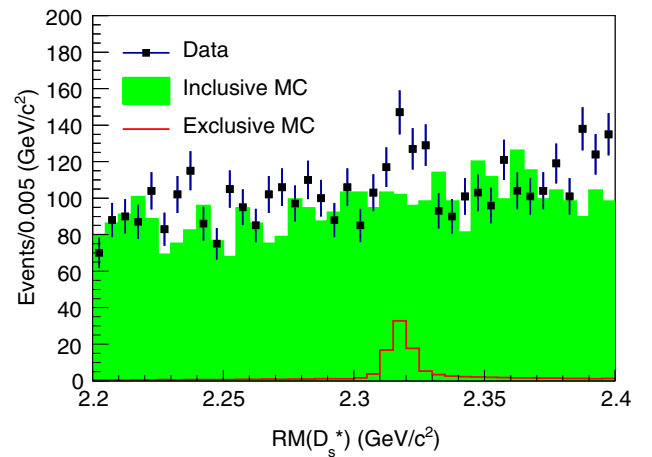


FIG. 1. Distribution of the  $D_s^{*+}$  recoil mass of the events from data (black dots) and inclusive MC sample (green histogram), which is normalized according to the integrated luminosity. The red curve shows the same distribution for  $D_s^{*+} D_{s0}^*(2317)^-$  events from MC simulation.

is observed. The inclusive MC sample, which does not include production of the  $D_{s0}^*(2317)^-$ , matches well with the background from data. In the inclusive MC sample, the remaining events are non- $D_s^{*+}$  events around the  $D_{s0}^*(2317)^-$  peak, including non- $D_s^{*+}$  events and miscombined  $\gamma D_s^+$  events, where the  $\gamma$  or  $D_s^+$  could come from other decay modes of  $D_s^{*+}$ . For the event with a real  $D_s^{*+}$ , such as  $e^+e^- \rightarrow D_s^{*+}D_s^{*-}$  or  $D_s^{*+}D_s^-$ , the recoil mass of  $D_s^{*+}$  is far away from the  $D_{s0}^*(2317)^-$  peak and has no influence in this analysis. In general, none of the known backgrounds can form a peak in the signal region. On the other hand, the technique to measure the absolute branching fraction  $\mathcal{B}(D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-)$  avoids the influence of the unknown three-body processes  $\gamma D_s^+ D_{s0}^*(2317)^-$  and  $\pi^0 D_s^+ D_{s0}^*(2317)^-$  even if they exist since they have an identical  $D_{s0}^*(2317)^-$  compared to the signal process  $D_s^{*+} D_{s0}^*(2317)^-$ .

The process  $e^+e^- \rightarrow D_s^{*+} D_{s0}^*(2317)^- \rightarrow D_s^{*+} \pi^0 D_s^-$  is studied via a further  $\pi^0$  reconstruction with two photons from the remaining showers in the EMC and  $D_s^-$  as the missing particle. If there are more than two photons, all combinations of  $\gamma\gamma D_s^{*+}$  are subjected to a 4C kinematic fit with mass constraints on the  $D_s^+$ ,  $D_s^{*+}$ ,  $\pi^0$  candidates and a missing  $D_s^-$ , requiring the  $\chi_{4C}^2$  to be less than 36.

The requirements on  $\Delta M_{K^+K^-\pi^+}$ ,  $\Delta M_{\gamma K^+K^-\pi^+}$ ,  $\chi_{2C}^2$  and  $\chi_{4C}^2$  are optimized with MC samples to obtain the best statistical precision of  $\mathcal{B}(D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-)$ . The  $D_s^{*+} D_{s0}^*(2317)^-$  signal is generated by assuming  $\mathcal{B}(D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-) = 0.9$  and  $\mathcal{B}(D_{s0}^*(2317)^- \rightarrow \gamma D_s^{*-}) = 0.1$  and normalized according to the number of signal events from data. The background is taken from a toy MC sample generated by fitting the recoil mass distribution of  $D_s^{*+}$  from data. The MC samples are analyzed with the same procedure as for data to obtain the branching fraction  $\mathcal{B}(D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-)$ . The requirements yielding the smallest relative statistical uncertainty are used in this analysis.

#### IV. MEASUREMENT OF THE ABSOLUTE BRANCHING FRACTION

Based on the above event selections, the  $e^+e^- \rightarrow D_s^{*+} D_{s0}^*(2317)^-$  events are divided in two subcategories: “ $\pi^0$ -tag succeeded” if at least one  $\pi^0$  is tagged and the event passed the 4C kinematic fit, and “ $\pi^0$ -tag failed” for the other events. The recoil mass distributions of the  $D_s^{*+}$  from the 2C kinematic fit of these two subcategories are shown in Fig. 2. These distributions are fitted simultaneously to measure the branching fraction of  $D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-$ .

The real  $D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-$  signal events could be categorized into both subsamples since the detection efficiency for  $\pi^0$  is 43.4%. On the other hand, potential background events, such as  $D_{s0}^*(2317)^- \rightarrow \gamma D_s^{*-}$  or other decay channels, could be reconstructed in the  $\pi^0$ -tag

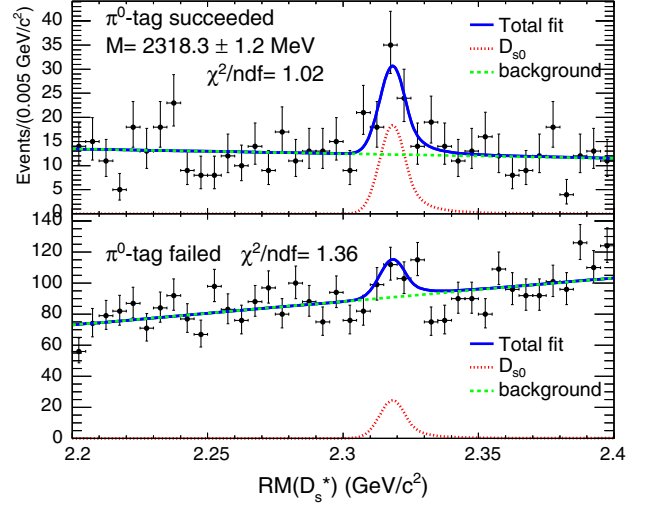


FIG. 2. Fit result for data at 4.6 GeV for the two subsamples,  $\pi^0$ -tag succeeded (top) and  $\pi^0$ -tag failed (bottom). The red dotted and green dashed curves show the fit results for signal and background, respectively, while the blue curve shows their sum.

succeeded sample too. Therefore, the number of  $D_{s0}^*(2317)^-$  signal events in the  $\pi^0$ -tag succeeded subsample,  $N_0$ , is expressed as

$$N_0 = N_{\text{tot}}/\epsilon_{\text{tot}} \cdot \mathcal{B} \cdot \epsilon_{\text{sig}} + N_{\text{tot}}/\epsilon_{\text{tot}} \cdot (1 - \mathcal{B}) \cdot \epsilon_{\text{bkg}}, \quad (1)$$

where the first and the second terms represent the contributions from  $D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-$  (with a branching fraction of  $\mathcal{B}$ ) and from the other  $D_{s0}^*(2317)^-$  decay mode (with a branching fraction of  $1 - \mathcal{B}$ ), respectively. Here the other decay mode means the potential peaking background mode  $D_{s0}^*(2317)^- \rightarrow \gamma D_s^{*-}$ , which is expected to be the dominant mode besides  $\pi^0 D_s^-$ , and any other decay modes are considered in the systematic uncertainty. The  $N_{\text{tot}}$  is the number of  $D_{s0}^*(2317)^-$  signal events in the full sample (the sum of  $\pi^0$ -tag succeeded and  $\pi^0$ -tag failed events),  $\epsilon_{\text{tot}}$  is the corresponding detection efficiency for the reconstructed  $D_s^{*+}$ ,  $N_{\text{tot}}/\epsilon_{\text{tot}}$  is the number of produced  $D_s^{*+} D_{s0}^*(2317)^-$  events,  $\epsilon_{\text{sig}}$  is the detection efficiency for  $D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-$  events being reconstructed in the  $\pi^0$ -tag succeeded sample including the branching fraction of  $\pi^0 \rightarrow \gamma\gamma$  [5], and  $\epsilon_{\text{bkg}}$  is the efficiency for non- $[D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-]$  events to be reconstructed in the  $\pi^0$ -tag succeeded sample. The efficiencies  $\epsilon_{\text{tot}}$ ,  $\epsilon_{\text{sig}}$  and  $\epsilon_{\text{bkg}}$  are obtained from MC simulations, and are 40.0%, 17.2%, and 5.8%, respectively.

From Eq. (1), we derive the absolute branching fraction  $\mathcal{B}(D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-)$  as

$$\mathcal{B} = \frac{N_0 - N_{\text{tot}}/\epsilon_{\text{tot}} \cdot \epsilon_{\text{bkg}}}{N_{\text{tot}}/\epsilon_{\text{tot}} \cdot (\epsilon_{\text{sig}} - \epsilon_{\text{bkg}})}, \quad (2)$$

where the branching fraction  $\mathcal{B}$  and  $N_{\text{tot}}$  are the free parameters in a simultaneous fit to the recoil mass

distributions of the  $D_{s^*}^{*+}$  in Fig. 2, and  $N_0$  is calculated using Eq. (1).

The shape for the  $D_{s^*}^{*+}(2317)^-$  signal is described with a Crystal Ball function [28] convolved with a Gaussian function, while the background is parametrized with a linear function. The parameters of the Crystal Ball function except for the mass are fixed to the values from a fit to the MC simulated  $D_s^{*+}D_{s^*}^{*+}(2317)^-$  sample, in which the  $D_{s^*}^{*+}(2317)^-$  is simulated with zero width. The Gaussian function is used to describe the data-MC difference in mass resolution, and the standard deviation is taken from a control sample of  $e^+e^- \rightarrow D_s^{*+}D_s^{*-}$  at 4.6 GeV. By reconstructing the  $D_s^{*+}$  from the process  $e^+e^- \rightarrow D_s^{*+}D_s^{*-}$ , it is found that the recoiling  $D_s^{*+}$  signal shape in MC simulation needs to be smeared by a Gaussian with the standard deviation of 0.9 MeV/ $c^2$  in order to match the data. The standard deviation of the Gaussian function in the fit to the  $D_{s^*}^{*+}(2317)^-$  signal is fixed to this value.

From the simultaneous fit, the total number of  $D_{s^*}^{*+}(2317)^-$  signal events is  $115 \pm 21$ , and the number of  $D_{s^*}^{*+}(2317)^-$  events in the  $\pi^0$  tag-succeeded subsample is  $46.8 \pm 9.4$ . The latter event yield is found to be 49.3 with a constraint that the branching fraction is no larger than 1. Using Eq. (2), the absolute branching fraction of  $D_{s^*}^{*+}(2317)^- \rightarrow \pi^0 D_s^-$  is measured to be  $1.00^{+0.00}_{-0.14}$ , with a constraint that the branching fraction cannot be larger than 1. The statistical uncertainty, 0.14, is estimated by covering the 68.3% C.L. from the likelihood distribution of the branching fraction. By comparing the difference of the log-likelihood with and without the  $D_{s^*}^{*+}(2317)^-$  signal in the fit and considering the change of the number of degrees of freedom, the statistical significance of the  $D_{s^*}^{*+}(2317)^-$  signal is estimated as  $5.8\sigma$ . The mass of  $D_{s^*}^{*+}(2317)^-$  is measured to be  $(2318.3 \pm 1.2)$  MeV/ $c^2$ .

The  $J^P$  of  $D_{s^*}^{*+}(2317)$  is  $0^+$ , so both the  $D_s^{*+}D_{s^*}^{*+}(2317)^-$  and the  $\pi^0 D_s^-$  systems are expected to be in a relative  $S$ -wave, and the angular distributions are expected to be flat. We define the signal region of  $D_{s^*}^{*+}(2317)^-$  as  $[2.31, 2.33]$  GeV/ $c^2$ , and the sideband regions as  $[2.28, 2.30]$  and  $[2.34, 2.36]$  GeV/ $c^2$  to estimate the contribution of background. Figure 3 shows the angular distributions of

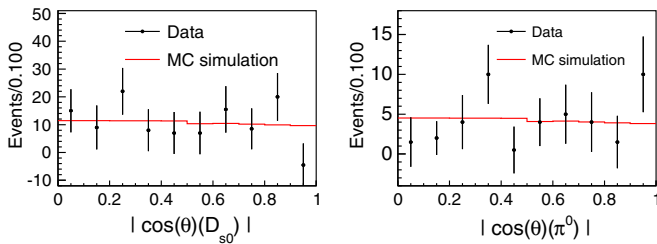


FIG. 3. Angular distributions of  $D_{s^*}^{*+}(2317)^-$  in the  $e^+e^-$  c.m. system (left) and of  $\pi^0$  in the  $D_{s^*}^{*+}(2317)^-$  c.m. system (right). Black dots and red lines represent the data after background subtraction and MC simulation, respectively.

$D_{s^*}^{*+}(2317)^-$  in the  $e^+e^-$  c.m. system and of  $\pi^0$  in the  $D_{s^*}^{*+}(2317)^-$  c.m. system. Both distributions are flat, as expected, and can be modeled by the MC simulations.

## V. SYSTEMATIC UNCERTAINTY STUDY

### A. Absolute branching fraction measurement

For the branching fraction measurement, many sources of systematic uncertainties cancel since the branching fraction is determined by the relative signal yields in the two subsamples. The main systematic uncertainties come from  $\pi^0$  reconstruction, the used signal and background shapes,  $\pi^0 D_s^-$  selections, the possible width of  $D_{s^*}^{*+}(2317)^-$ , and potential peaking backgrounds.

The uncertainty on  $\pi^0$  reconstruction is taken as 0.7% from a study of  $\psi(3686) \rightarrow J/\psi \pi^0 \pi^0$  and  $e^+e^- \rightarrow \omega \pi^0$  by considering the momentum dependency of  $\pi^0$ . In the nominal fit, the signal shape is parametrized by a Crystal Ball function with a tail due to the ISR effect. Given that the energy dependent cross sections of  $e^+e^- \rightarrow D_s^{*+}D_{s^*}^{*+}(2317)^-$  are not measured with high precision, the systematic uncertainty should be studied conservatively. We vary the signal shape to a Gaussian with all parameters free, and the relative difference in the branching fractions, 5.0%, is taken as systematic uncertainty. The background in the nominal fit is parametrized as a linear function. We change this shape to a second order polynomial function and take the relative difference in branching fractions, 7.4%, as systematic uncertainty due to background shape.

For  $\pi^0 D_s^-$  selection, we perform a kinematic fit, which could cause a systematic bias in the efficiency between data and MC simulation. To study this difference, we correct the helix parameters of the charged tracks in MC simulation [29]; the difference in  $\chi^2$  distribution between data and MC simulation becomes negligibly small according to other studies [30]. We take half of the difference in the ratio of detection efficiencies  $\epsilon_{\text{sig}}$  and  $\epsilon_{\text{tot}}$  between MC simulations with and without this correction as systematic uncertainty (3.1%). The nominal result is based on the corrected MC simulation.

The width of  $D_{s^*}^{*+}(2317)$  is unknown and cannot be measured in this analysis due to limited statistics. In the nominal fit, we use the shape from MC simulation of  $D_{s^*}^{*+}(2317)^-$  with a zero width to describe the signal. The upper limit on the width of  $D_{s^*}^{*+}(2317)^-$  is estimated as 3.8 MeV at 95% C.L. from previous experiments [5]. In an alternative fit, we change the width of  $D_{s^*}^{*+}(2317)^-$  to 3.8 MeV; use the same Gaussian function to convolve the shape from MC simulation; and take the difference in the branching fraction, 5.3%, as systematic uncertainty.

In Eq. (2), the peaking background is considered, and the result of the fit shows that its contribution is negligible. For the signal mode,  $D_{s^*}^{*+}(2317)^- \rightarrow \pi^0 D_s^-$ , the tagged  $\pi^0$  could also come from  $D_s^-$ . This kind of event is regarded as signal, and its contribution is included in the definition of the



TABLE I. Summary of relative systematic uncertainties in  $\mathcal{B}(D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-)$ .

Source	Uncertainty (%)
$\pi^0$ reconstruction	0.7
Signal shape	5.0
Background shape	7.4
$\pi^0 D_s^-$ selections	3.1
Width of $D_{s0}^*(2317)^-$	5.3
Peaking backgrounds	8.5
Total	13.8

efficiency, which is estimated from the MC simulation of  $e^+e^- \rightarrow D_s^{*+} D_{s0}^*(2317)^- \rightarrow D_s^{*+} \pi^0 D_s^-$  with  $D_s^-$  decaying to all possible modes. All peaking backgrounds come from other decay modes of  $D_{s0}^*(2317)^-$ . To study the possible contribution conservatively, we simulate the potential peaking backgrounds,  $D_{s0}^*(2317)^- \rightarrow \gamma D_s^{*-}, \gamma \gamma D_s^-$  and  $\pi^+ \pi^- D_s^-$  exclusively. The upper limits on the ratios  $\Gamma(\gamma D_s^{*-})/\Gamma(\pi^0 D_s^-)$ ,  $\Gamma(\gamma \gamma D_s^-)/\Gamma(\pi^0 D_s^-)$ , and  $\Gamma(\pi^+ \pi^- D_s^-)/\Gamma(\pi^0 D_s^-)$  are estimated as 0.059, 0.18, and 0.006, respectively [5]. The total systematic uncertainty in  $\mathcal{B}(D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-)$  is conservatively estimated to be 8.5%.

All the above systematic uncertainties are listed in Table I. Assuming all of them are independent and adding them in quadrature, we estimate a total systematic uncertainty of 13.8% in the branching fraction. Since the  $\mathcal{B}_{D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-}$  is at the upper bound, we assign a  $-0.14$  systematic uncertainty in it.

## B. Mass measurement

The systematic uncertainties in the mass measurement of  $D_{s0}^*(2317)^-$  come from mass calibration, signal shape, background shape, and c.m. energy determination. For the mass calibration, we use the control sample  $e^+e^- \rightarrow D_s^{*+} D_s^{*-}$  at 4.6 GeV and compare the mass of the recoiling  $D_s^{*-}$  with the world average value [5]. The same event selections and fit procedure as for  $D_s^{*+} D_{s0}^*(2317)^-$  are used for  $D_s^{*+} D_s^{*-}$ , and the shape of the missing  $D_s^{*-}$  is parametrized as a Crystal Ball function convolved with a Gaussian function. The difference in the mass of  $D_s^{*-}$  between data and the world average value [5], which includes the contribution of the uncertainty on c.m. energy, 1.2 MeV/ $c^2$ , is taken as systematic uncertainty. The uncertainties in signal and background shapes are studied with the same method as for the systematic uncertainty study in branching fraction measurement. The results show that these systematic uncertainties are negligible.

## VI. SUMMARY AND DISCUSSION

In summary, we observe the  $D_{s0}^*(2317)^-$  signal in the process  $e^+e^- \rightarrow D_s^{*+} D_{s0}^*(2317)^-$  from a data sample at a c.m. energy of 4.6 GeV. The statistical significance of the

$D_{s0}^*(2317)^-$  signal is  $5.8\sigma$ , and the mass is determined to be  $(2318.3 \pm 1.2 \pm 1.2)$  MeV/ $c^2$ . The absolute branching fraction of  $D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-$  is measured for the first time to be  $1.00_{-0.14}^{+0.00}(\text{stat})_{-0.14}^{+0.00}(\text{syst})$ , where the uncertainties are statistical and systematic, respectively. The result shows that  $D_{s0}^*(2317)^-$  tends to have a significantly smaller branching fraction to  $\gamma D_s^{*-}$  than to  $\pi^0 D_s^-$ , and this differs from the expectation of the conventional  $\bar{c}s$  hypothesis of  $D_{s0}^*(2317)^-$  [13], which predicts that  $D_{s0}^*(2317)^-$  should have a branching fraction of  $\gamma D_s^{*-}$  at around 15% or even larger, but agrees well with the calculation in the molecule picture [14], which shows that the branching fraction of  $\pi^0 D_s^-$  is in a range of 93–100%. In the future, with more data accumulated at BESIII or with a fine scan from PANDA [31], the width of  $D_{s0}^*(2317)^-$  could be measured. Combined with the absolute branching fractions of  $D_{s0}^*(2317)^- \rightarrow \pi^0 D_s^-$  and  $\gamma D_s^{*-}$ , we may shed light on the nature of  $D_{s0}^*(2317)^-$ .

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